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Analysis and Experiment of MEMS based Micropump for Microfluidic Application

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Abstract

In this paper, we have addressed the issues related to the design and simulation of MEMS based silicon micro-needles for insertion of fluid into the dermis and subcutaneous fat layer of human skin. Microelectromechanical systems (MEMS) are uncovered to an assortment of liquid environments in applications such as chemical and biological sensors and microfluidic devices .Green interactions between liquids and microscale structures can lead to volatile performance of MEMS in liquid environments. In this paper, the design and fabrication of a multi- material high-performance micropump is presented. The micropumps are fabricated using MEMS fabrication techniques, comprised of silicon and Pyrex micromachining and bonding. Manufacturing steps such as three small bulk cylindrical piezoelectric material elements that are integrated with micro-fabricated silicon-on-insulator (SOI) and glass micromachined substrates using eutectic bonding and anodic bonding processes were successfully realized and provide a robust and scalable production technique for the micro pump. Exceptional flow rates of 0.1 ml/min with 1 W power consumption based on piezoelectric stack actuation achieved by appropriate design optimization.

Keywords: MEMS, SOI, Pyrex micromachining, Eutectic bonding, Anodic bonding

1.Introduction

There are many advantages to miniaturizing systems for chemical and biological analysis[1]. Recent interest in this area has led to the creation of several research programs, including a Micro Gas Analyzer[20]. The aim of this project is to develop a new approach for detecting biological and chemical agents. Currently available portable drug delivery micropump[2] are expensive, slow, bulky, and consume significant power. New approaches that have the potential for instantaneous detection in the field that are low cost, portable, and consume very little power would be extremely useful. The possible advantages and applications of such a device are numerous: it could be deployed in remote locations in laboratories and industry for chemical and biological agent analysis or as safety leakage detectors, and of course in the field in the hand or on the uniform of an inspector or intelligent robot that is able to communicate with a base station. The Micro Gas Analyzer[9] will consist of several key components that will themselves also be very useful in other areas of research, as well as find applications in industry.

This research work will focus on demonstrating that a MEMS Micro Vacuum Pump to meet the specifications can be made; these specifications call for the generation of 0.1 ml/min flow rate with 1 W power consumption based on piezoelectric stack actuation[19]. Typical large-scale instruments operate at rather low pressures (< μ N/m^2) because of the requirement that ions suffer few collisions during mass analysis

One of the first micropumps was developed by Jan Smits in the early 1980s for use in insulin delivery systems[3]. Since then micropumps have been developed for medical applications**,** microelectronic device cooling and chemical and biological analysis among other applications (e.g. space exploration) [24].

The two main types of pumps are

Displacement pumps - in which boundaries moving the fluid create pressure differentials[

Dynamic pumps - in which energy is added to the fluid to increase its momentum or its pressure

The typical reciprocating displacement micropump with a pump chamber and diaphragm, an actuator, and two passive check valves at the chamber input and output. When the diaphragm is actuated to increase the pump chamber volume fluid[10] is "sucked" into the pump, and when the diaphragm is actuated to decrease the pump chamber volume fluid is "pushed out" of the pump. Check valves open and close depending on the pressure differential across them and the direction of fluid flow is shown in the Fig - 1

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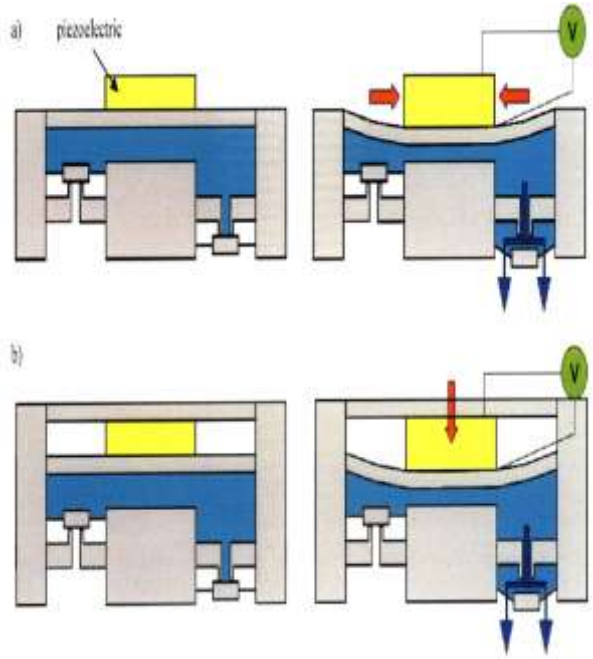


FIG-1.a) piezoelectric actuator in the lateral-strain configuration. b) Piezoelectric actuator in the axial strain configuration.

2.Micropump Design

To meet our goals for speed, power, and vacuum generation the appropriate choice was to use an active valve reciprocating displacement micropump design[4]. The majority of micro-valves are classified as either active or passive. Passive valves (also called check valves) are not actuated by an external control unit; they are opened by pressure differentials and the direction of through-flow, and are mostly mechanical flap structures[25] or flexible diaphragms.

Our micropump design consists of 5 layers (i.e. 5 wafers) but layers **1-3** define the ultimate performance since they contain the channels, chambers, pistons, and tethers connecting the pistons to the side walls. The aim of this thesis is to focus on the design and fabrication of these layers for testing. Layer 4 contains the piezos[12] to drive the pistons and layer 5 provides structural support[3], both of which can be integrated to make the final device once a suitable design for layers 1-3 is found.

There are three main parts to the test setup: the fluidic connections[21], electronics and circuitry, and computer software[5]. We begin by looking at the fluidic connections[13]. The micropump dies to be tested are clamped using optical clamps[14] onto the testing platform. Each pump die has 5 access ports: one input port, one output port (interchangeable)[6], and three actuation ports[15] for the input/output valves and the pump chamber. O-rings [23]help seal the pump die ports against the testing platform.

The final process flow corresponds to a set of 8 masks and the CAD[7] layout shown in Fig -2

2.1.MEMS Micropump Layer Design

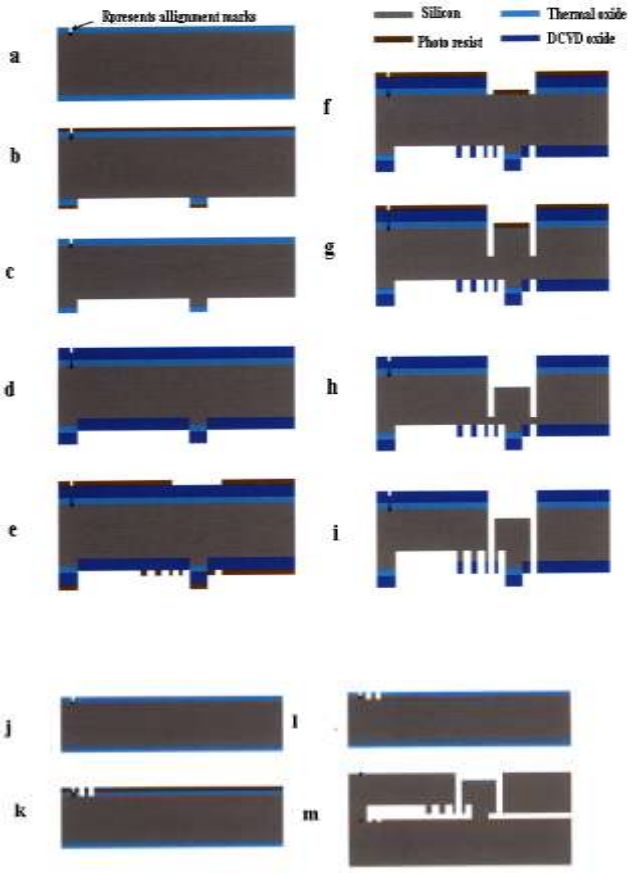


FIG- 2.(a–m) Different CAD Layout of the micropump Layer

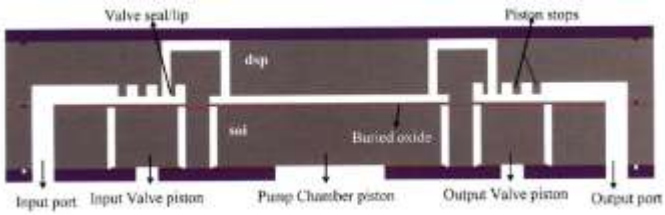


FIG- 3 DSP LAYER

2.2.Layer 2 - DSP(450um Si) (FIG 3)

1.Grow thermal oxide (0.3um) - preferably buy wafers with thermal oxide pre-grown[8]
2. HMDS wafers, deposit thin resist on both sides, pre-bake, photo **M1 (alignment marks)** on topside, develop, post-bake
3. BOE for 4minutes, spin-dry wafers
4. Alignment mark etch topside using Almark recipe on STS2 or STS3 for 10sec
5. Strip resist using piranha, spin-dry wafers

6. HMDS wafers, deposit thin resist on both sides, pre-bake, photo **M1 (alignment marks)** on bottomside making sure they line up with topside alignment marks, develop, post-bake
7. BOE for 4minutes, spin-dry wafers
8. Alignment mark etch bottomside using Almark recipe on STS2 or STS3 for 10sec
9. HMDS wafers, deposit thin resist on both sides, pre-bake, photo **M3 (6um chamber etch)** on bottomside, develop, postbake
10. BOE for 4minutes, spin-dry wafers
11. Etch pump chamber from bottom using Jbetch in STS3 till 6um chamber depth is obtained (measure using dektak profilometer)[11], rotate wafers at least 4 times during etch
12. Strip resist using piranha, spin-dry wafers
13. Deposit 4um of thick oxide on both sides using ICL DCVD
14. HMDS wafers, deposit thick resist on both sides, pre-bake, photo **M5 (valve lip and posts)** on bottomside, photo **M3 (cross channels)** on topside, develop, post-bake
15. Etch 4.3um of oxide on both sides using ICL AME5000
16. Strip resist using piranha, spin-dry wafers[22]
17. HMDS wafers, deposit thick resist on both sides, pre-bake, photo **M4 (through holes)** on topside, develop, post-bake
18. Etch through holes from the top by (450-30-Channel width) microns using recipe MIT69A on STS2, make sure to rotate wafers often for etch uniformity
19. Strip resist using piranha, spin-dry wafers
20. Ash wafers for 1.5hours
21. HMDS wafers, deposit thick resist on bottomside, post-bake
22. Etch through holes and channels from the top by the Channel width microns making sure to stop short of ~24um of breaking through the bottomside using recipe MIT69A on STS2, make sure to rotate wafers often for etch uniformity
23. Strip resist using piranha, spin-dry wafers
24. HMDS wafers, deposit thin resist on topside, post-bake
25. Apply blue-tape to topside
26. Etch from the bottom by slightly greater than 24um to create the valve lips, support posts, and open up the valve to pump chamber channels. Use recipe MIT69A on STS2, make sure to rotate wafers often for etch uniformity
27. Once complete place wafer in acetone till blue-tape comes off
28. Strip resist using piranha, spin-dry wafers
29. Ash wafers for 1.5hours

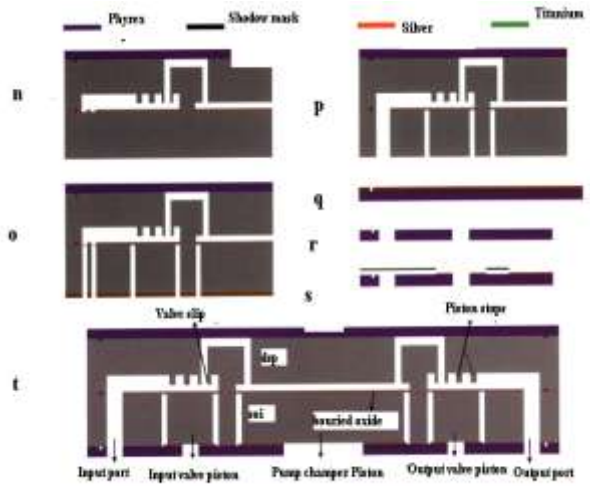


FIG - 4(n – t) Different Layout of the micropump SOI Layer

2.3.Layer 3 - SOI (450um Si) FIG 4)

1.Grow thermal oxide (0.3um) - preferably buy wafers with thermal oxide pre-grown
2. HMDS wafers, deposit thin resist on both sides, pre-bake, photo **M1 (alignment marks)** on topside, develop, post-bake
3. BOE for 4minutes, spin-dry wafers
4. Alignment mark etch topside using Almark recipe on STS2 or STS3 for 10sec
5. Strip resist using piranha, spin-dry wafers
6. HMDS wafers, deposit thin resist on both sides, pre-bake, photo **M1 (alignment marks)** on Bottom side making sure they line up with topside alignment marks, develop, post-bake
7. BOE for 4minutes, spin-dry wafers
8. Alignment mark etch bottom side using Al mark recipe on STS2 or STS3 for 10sec
9. HMDS wafers, deposit thin resist on both sides, pre-bake, photo **M7 (input/output ports)** on topside, develop, post bake
10. BOE for 4minutes, spin-dry wafers
11. Etch input/output ports from the top by 10um until the buried oxide layer is reached using recipe MIT69A in STS2, rotate wafers at least 4 times during etch
12. Strip resist using piranha, spin-dry wafers
13. Deposit 4um of thick oxide on the bottom side using ICL DCVD
14. HMDS wafers, deposit thick resist on both sides, pre-bake, photo **M6 (tethers)** on Bottom side, develop, post-bake
15. Etch 4.3um of oxide on bottom side using ICL

AME5000
16. Strip resist using piranha, spin-dry wafers
17. HMDS wafers, deposit thin resist on topside, post-bake
18. Apply blue-tape to topside
19. Etch tethers from the bottom till the buried oxide is reached and the right tether width/fillet profile is obtained. Use recipe MIT69A on STS2. Make sure to rotate wafers often for etch uniformity. Once any tether is complete paint it with resist by hand and let it dry in air for 3hours before proceeding with etching other tethers - don't use oven. 20. Once tethers all completed place wafer in acetone till blue-tape comes off
21. Strip resist using piranha, spin-dry wafers
22. Ash wafers for 1.5hours

2.4.Bottom Support Pyrex Layer

1.Get alignment marks, input/output and actuation ports machined by Bullen Ultrasonics[16] using **M8 (pyrex holes)**
2. Make a shadow mask for the pyrex wafer: HMDS a blank Si wafer, deposit double layer of thick resist on the topside, pre-bake, photo **M9 (shadow mask)** on topside, develop, post- bake, mount on quartz wafer, and etch through the wafer till the shadow mask is complete using recipe Jbetch on STS2 or STS3
3. Un amount shadow mask from quartz wafer and clean using piranha, then spin-dry wafers[17]
4. Align shadow mask to quartz wafer using bonding aligner and water droplets (to help wafers stick together)
5. Deposit 0.02um of Titanium adhesive layer followed by 0.2um of Silver in Ebeam[19]

2.5.Bonding & Cutting

6. HF strip all oxide from DSP Layer 2
7. BOE strip all oxide from SOI Layer 3 - at the same time the buried oxide will also be removed (don't etch more than buried oxide thickness so make sure that all other oxide on the wafer is already thinner before beginning this step). Can't use HF on this layer.
8. Spin dry clean the pyrex bottom layer
9. RCA clean Layer 2, Layer 3, and a blank capping Si wafer (no HF)
10. Silicon direct bond blank capping wafer to Layer 2 to Layer 3
11. Anneal the 3 layer silicon stack for lHour at 950degrees Celcius
12. Anodically bond stack to pyrex bottom layer
13. Die-saw the micropump dies using thickest black blade (use die-saw tape on both sides to prevent water/slurry from entering the devices)

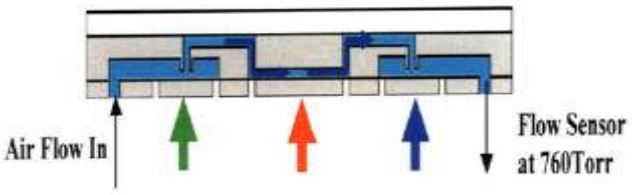
3.Results and Hypothesis

This round of fabrication led to a fully functioning set of vacuum micropumps. Using the test setup we performed the main set of tests on these devices:

Test 1: Check for valve and pump chamber leaks **by** actuating the pistons and measuring any flows at the Input or output ports
Test 2: Check that all pistons can shut down flow **by** applying an external pressure source at the input and measuring the flow rate at the output as each of the pistons is actuated
Test **3:** Measure the flow rate through the device as a function of the pressure differential applied across it
Test 4: Measure the micropump generated flow rate via the **6** stage pumping cycle shown below, as a function of operating frequency
Test **5:** Measure the micropump generated vacuum at a frequency of operation in the micropump's operating range indicated **by** Test 4

4.Pump Models and Characterization

To test the pistons we applied a constant pressure source at the input port and measured the output flow rate using a mass flow meter as we attempted to actuate the pistons [2]. We only applied positive pressures to actuate the pistons (no vacuum to pull them down). Ideally for actuation[18] pressures above the input



High pressure gas applied below pistons for actuation

pressure the pistons should actuate shut and the output flow should drop to zero

FIG - 5. Layout of the Micropump flow model

Air is input at the input port and the output flow rate is measured using a flow sensor. As the three pistons are actuated (indicated by the transparent vertical bars) we expect to see a complete cut off of any flow (green data for the input piston, red for the chamber piston, and blue for the output piston). Note that the input and output pistons do work to some degree but that the pump chamber tether is leaking air is shown in the Fig- 5 and Fig - 6

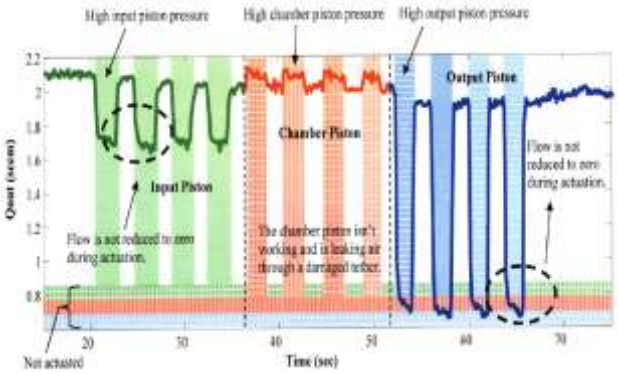


Fig- 6. Simulation results of high pressure flow in the micropump

5.Simulation Result

The measured flow rate as a function of the operating frequency (6 stage pumping cycle) is plotted in Fig -7 which gives the Exceptional flow rates of 0..25 ml/min based on piezoelectric stack actuation

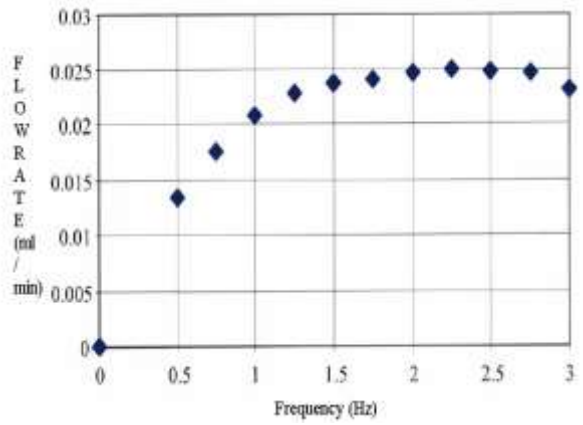


FIG-7 Simulation results of Cumulative Flow rate as a function of the frequency

6.Conclusion

The design of air micropumps useful models and the coventorware software tools for the analysis of plate/thin film bending/stress and for the analysis of fluid flow in MEMS devices. A complete pneumatic testing platform and effective testing techniques for the characterization of micropumping devices. The experimental data demonstrating how the various design parameters influence pump and valve performance. Finally an attractive design that would bring us closer to meeting the micropump for drug delivery system goals also Valve leakage data for various valve designs was collected and compared with models and a micro pump capable of generating vacuum below atmosphere was demonstrated at different frequency operation. This pump may be designed pneumatically-driven with self contained actuation

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